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Lethal, Sublethal and Antifeedant Effects of Azadirachtin on Some Major Insect-pests: A Review

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ABSTRACT

Azadirachtin, a key bioactive compound derived from the neem tree (*Azadirachta indica*), has gained prominence as an eco-friendly alternative for controlling insect pests, which pose significant threats to crops. It has emerged as a versatile tool in integrated pest management strategies having a multi-faceted impact on insect pests. Azadirachtin affects the development of insect pests by disrupting their growth, moulting and pupation processes, Furthermore, the antifeedant properties of azadirachtin lead to deterring of feeding in target pests,altering insect feeding habits. The potential synergies and trade-offs of utilizing azadirachtin in conjunction with other control methods could optimize its effectiveness while minimizing ecological impact.The comprehensive insights presented herein contribute to the refinement of sustainable pest control strategies, offering guidance for future research directions and the implementation of azadirachtin in environmentally conscious agricultural practices.

Key words: Antifeedant, Azadirachtin, Development, Insect pests, Mortality.

Conventional synthetic insecticides have long played an important role in increasing agricultural production (Popp *et al.,* 2013). In the absence of practical and efficient alternatives, insecticides will continue to be a key component in pest management programmes and will remain essential for preventing food insecurity in meeting the needs of present and future generations (Deravel *et al.,* 2014). The extensive use of these insecticides has led to risks and hazards to human and environmental health as well as increasing resistance development in target pest insects through the exertion of selection pressure (Helps *et al.,* 2017; Jars *et al.,* 2018; Ojha *et al.,* 2018). The real challenge lies in the search for alternative control methods that reduce the risks associated with conventional synthetic insecticides (Khater, 2012).The term biopesticides or natural pesticides is the result of this search, which are environmentally friendly and have low toxicity to non-target organisms (Sharma and Gaur, 2019; Morakchi *et al.,* 2021; Tulashie *et al.,* 2021).

Azadirachta indica is an important limonoid-producing plant from the Meliaceae family that has long been recognised as a source of environmentally friendly biopesticides (Senthil-Nathan, 2013; Dey *et al.,* 2017). It has low toxicity to mammals and is effective even at low concentrations. Due to the complexity of its active components in *A. indica*, the likelihood of resistance development by these botanicals is considered low (Vendramim and Castiglioni, 2000; Roel *et al.,* 2010). *A. indica* has been reported to attack more than 300 insect pests (Mordue and Blackwell, 1993). It can cause effects such as repellency, developmental arrest and retardation, deformations, ecdysis, reduction in fertility and fecundity, changes in behaviour and physiology of insect pests resulting in mortality. The extent of the effects and the reaction time depend on the dose and the duration of exposure (Martinez 2002; Roel *et al.,* 2010). *Melia azedarach* L., which is closely related to *A. indica*, also contains several limonoids and shows excellent insecticidal activity (Charleston *et al.,* 2004). The most important active limonoid in both Meliaceae trees is azadirachtin, which acts as an antifeedant and growth regulator for insects (Senthil-Nathan, 2013).

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Toxicity of various botanicals

Neem seed oil and methanolic neem leaf extracts were effective insecticides against fall armyworm (*Spodoptera frugiperda*), as per Tulashie *et al.* (2021). Neem seed oil LC_{50} values were 1.7, 0.97 and 0.68% after 2, 6 and 12 hours respectively. Methanolic neem leaf extract LC_{50} values were 2.67, 2.62 and 1.64% for the same time periods. Concentrations of 3.0% and 5.0% resulted in 100% mortality after 6 and 12 hours. Silva *et al.* (2015) found neem seed cake more toxic than neem leaf extract, with LC_{50} values of 0.13% and 0.25% respectively.

Duarte *et al.* (2019) observed reduced survival in *S. frugiperda* larvae with increasing neem oil concentrations. Mortality at 50% and 90% occurred at 9,500 and 17,230 ppm. Roel *et al.* (2010) noted 100% mortality in *S. frugiperda* larvae at a 0.4% neem oil dose in the first instar stage.

Sisay *et al.* (2019) found higher mortality in *S. frugiperda* larvae with 5.0g of *A. indica* bio-insecticide in various conditions. Lima *et al.* (2010) reported the highest larval mortality with commercial neem formulations (Natuneem® and Neemseto®) against *S. frugiperda.* Azadirachtin toxicity against coconut spike moth, *Tirathabarufivena*, (Walker) (Lepidoptera: Pyralidae) was assessed for stomach and contact effects. Stomach toxicity ranged from 28.79 to 92.70 mg/L across instars, while contact toxicity ranged from 12.85 to 32.34 mg/L. LC50 values indicated first instars were 1.53 to 3.22 times more susceptible than subsequent instars (Zhong *et al.,* 2017).

Sharma and Singh (2014) examined neem leaf extracts in methanol and hexane for toxicity against the diamondback moth, *Plutellaxylostella*. Tested at concentrations ranging from 0.5% to 3%, even the lowest concentration (0.5%) resulted in significantly higher larval mortality (61.67%) compared to the control (13.33%). Neem methanol extracts induced 100% mortality at 3% concentrations for first and second instar larvae. Mortality exceeded 50% at 2.5% and 2% NME concentrations during the first and second larval stages. Neem hexane extract (NHE) at 1.5% concentration showed notably higher lethal impact than the control, reaching 51.67% mortality at 3%. Higher neem leaf extract concentrations led to a maximum larval mortality of 52.5% for *P. xylostella* (Sow and Diarra 2013).

Zada *et al.* (2018) assessed azadirachtin concentrations (0.31, 0.50, 0.60 and 1.0%) against third and fourth instar larvae of *P. xylostella* in choice and no-choice tests. LC50 values in the choice test were 0.66 to 0.37 µg/ml for third instar and 0.55 to 0.34 µg/ml for fourth instar larvae at 24 to 72 hours. No-choice test LC50 values were 0.63 to 0.29 µg/ml for third instar and 0.52 to 0.31 µg/ml for fourth instar larvae at 24 to 72 hours, showing descending toxicity. Paramita*et al.* (2018) found *A. indica* seed extract 50 EC effective against *Spodoptera litura* larvae, with mortality rates of 76.7, 86.7 and 93.3% at concentrations of 2, 3 and 4% respectively.

Sub-lethal influences of different botanicals on larvae, pupae and adults

The assessment of insecticides' sub-lethal effects on insect biology is critical for integrated pest management programmers because while sub-lethal concentrations do not kill insects, they can reduce insect populations in subsequent generations by interfering with biological traits.

Sub-lethal influences on the growth and development stages of the *S. frugiperda* larvae, pupae and adults may also cause the malformation of adults, pupal-adult intermediates and larval-pupal intermediates.

Larval duration

Duarte *et al.* (2019) tested three *A. indica* oil concentrations (5000, 10000 and 15000 ppm) mixed with the artificial diet against *S. frugiperda*. At the highest concentration (15000 ppm), there was a significant 76% increase in the larval period of *S. frugiperda* compared to the control group. Roel *et al.* (2010) observed sub-lethal effects of neem oil on *S. frugiperda* development, noting increased larval durations (23.47 days at 0.05%, 21.89 days at 0.006%) compared to the control (21.12 days). Malik *et al.* (2017) found prolonged larval periods (15.47, 16.40, 17.23, 18.13 days) for *S. litura* fed on cauliflower leaves treated with neem oil concentrations (1000, 1500, 2000, 2500 ppm).

Azadirachtin's impact on African cotton leafworm, *Spodopteralittoralis*, (Boisduval) (Lepidoptera: Noctuidae) was assessed in the laboratory. Third instar larvae on artificial diet with 0.3 and 0.6 ppm azadirachtin had a two-day longer instar duration compared to controls (Martinez and Emden 2001). Simmonds *et al.* (1990) noted insect mortality, especially during moulting, with higher azadirachtin concentrations in *S. littoralis*. Abedi *et al.* (2014) reported a significant 21.3-day extension in larval duration for cotton bollworm, *Helicoverpaarmigera*, (Hubner) (Lepidoptera: Noctuidae) exposed to azadirachtin (8.8 µg *a.i.*/mL) in artificial diet. Farias *et al.* (2019) observed prolonged larval periods (18.69 and 15.43 days) in *H. armigera* with neem-based formulations compared to the control's 15.78 days. Singh *et al.* (2006) found *Melia azedarach* extracts increased larval durations (7.0-7.8 days) for second instar larvae of *P. xylostella* at concentrations of 1.47, 1.79 and 2.29% compared to the control (6.3-6.5 days). Sub-lethal concentrations led to a significant prolongation of development from second to fourth instar larvae.

Pupal duration

Duarte *et al.* (2019) studied sub-lethal effects on *S. frugiperda* development, finding *A. indica* oil concentrations of 5000 and 15000 ppm increased pupal durations to 11.1 and 12.3 days, respectively, compared to 10.5 days in the control. Merkey *et al.* (2011) noted reduced metamorphosis and pupal development with increased pupal duration in low-nutrition conditions for *S. frugiperda.*

S. litura larvae exposed to neem oil concentrations (500-2500 ppm) by Malik *et al.* (2017) showed increased pupal periods (7.10-9.23 days) compared to the control (6.80 days). Roel *et al.* (2010) reported neem oil concentrations (0.006 and 0.05%) significantly increased *S. frugiperda* pupal duration (11.08-11.67 days). Abedi *et al.* (2014) recorded a 23.1-day prolongation in *H. armigera* pupal duration with azadirachtin (8.8 µg a.i./ml).

Gulzar *et al.* (2018) found *A. indica* methanolic extract affected *Earias vittella* (Fabr.) (Lepidoptera: Noctuidae) pupal duration significantly at sub-lethal concentrations (1.59 and 5.50%), with durations of 15.61 and 12.51 days, respectively, compared to the control (9.42 days). Schmidt *et al.* (1997) observed an extension in *Agrotisipsilon* (Hufn.) (Lepidoptera: Noctuidae) pupal period, averaging 20.3 days at 50 ppm extract concentration, compared to 14.6 days in the control. Concentrations of 15, 25 and 50 ppm showed no significant differences in pupal period.

Pupal weight

Singh *et al.* (2006) found *M. azedarach* concentrations (1.47, 1.79, 2.29%) significantly reduced pupal weight (36.0-38.4 mg/10 pupae) compared to the control (54.4-56.0 mg/10 pupae) in *P. xylostella*. In *A. ipsilon*, *Melia* extract concentrations (10, 15, 25, 50 ppm) reduced pupal weight (165-327 mg) compared to control (400 mg). *S. littoralis*pupal weight decreased at 15, 25 and 50 ppm of *Melia* extract (267-343 mg) compared to control (397 mg). Higher concentrations prevented larvae from reaching pupal stage (Schmidt *et al.,* 1997).

S. littoralis larvae treated with azadirachtin (0.5, 0.1, 0.05 ppm) showed reduced pupal weight (Martinez and Emden, 2001). Abedi *et al.* (2014) found azadirachtin (8.8 µg a.i./ml) reduced pupal weight in *H. armigera* (205.1 mg) compared to untreated groups (298.3 mg). Ma *et al.* (2000) reported sub-lethal effects of azadirachtin on *H. armigera* pupal weight. *A. indica* extract significantly decreased pupa weight of *E. vittella* (50.21 and 39.25 mg) compared to control (63.25 mg) (Gulzar *et al.,* 2018). Neem oil concentrations (0.006% and 0.05%) in *S. frugiperda* reduced pupal weight (0.156-0.191 g) compared to control (0.194 g) (Roel *et al.,* 2010). Duarte *et al.* (2019) exposed *S. frugiperda* larvae to neem oil concentrations (5000, 10000, 15000 ppm) resulting in decreased pupal weight (151.4-182.7 mg) compared to control (214.0 mg). Lima *et al.* (2010) observed a 19% lower pupal weight in *S. frugiperda* larvae exposed to *A. indica* oil (500 ppm) compared to untreated insects. Malik *et al.* (2017) noted pupal weight reduction in *S. litura* at neem oil concentrations (500-2500 ppm). Ahmad *et al.* (2015) evaluated neem-based insecticides on *H. armigera*, observing decreased pupal weight with neem oil (255.3 mg) compared to the control (278.6 mg).

Adult emergence

Abdel-Aziz *et al.* (2013) studied sub-lethal effects of bitter and neem oils on *S. littoralis*. Second and fourth instar larvae were exposed to sub-lethal concentrations of bitter oil (0.116, 0.184%) and neem oil (0.153, 0.21%). Adult emergence decreased to 12.29% for neem oil in pretreated fourth instars and 25% for bitter oil compared to 84% in the control. Bakr *et al.* (2012) noted increased overall adult deformities in *S. littoralis* with neem treatment (66.1%) in second instars and bitter treatment (50, 43.34%) in fourth and second instars, respectively, compared to the 8% control. Neem-based formulations (Neemarin, Neemazal, Neemix, Neem oil) significantly reduced *H. armigera* adult emergence (53.7%) compared to the control (90%) (Ahmad *et al.,* 2015). Singh *et al.* (2006) found *M. azedarach* extracts from different regions of India significantly reduced adult emergence in *P. xylostella* compared to the untreated group.

Adult size

Duarte *et al.* (2019) noted a 13and 63% reduction in wing length in *S. frugiperda* larvae treated with the highest neem oil concentrations (10,000 and 15,000 ppm) via artificial diet. The percentage of deformed adults increased with higher neem oil concentrations. Jones (2014) observed reduced forewing length, wing shape, body size and diminished flight in *S. frugiperda*. Singh *et al.* (2006) found *P. xylostela* adults emerging from *M. azedarach* extract treatments exhibited reduced size, highly twisted and fringed wings, hindering normal flight and mating. Zanuncio *et al.* (2016) studied sub-lethal effects of neem oil concentrations (0.5-50%) on the stink bug *Podisus nigrispinus* (Dallas) (Heteroptera: Pentatomidae) adults. Abnormalities ranged from 2.5 to 30.8%, increasing with higher neem oil concentrations. Main deformations included reduced hemelytra size, fewer veins, decreased membranous wing area, asymmetric scutellum and leg extension and folding.

Adult longevity

Duarte *et al.* (2019) observed reduced adult longevity in *A. indica* oil-exposed *S. frugiperda*, with males and females living 5.1 and 6.7 days at 5000 ppm neem oil compared to the control (9.4 and 11.9 days). Lima *et al.* (2010) reported decreased longevity in *S. frugiperda* adults fed on neem oil-treated corn leaves. Bruce *et al.* (2004) found neem oil reduced adult longevity in African pink stem borer, *Sesamia calamistis* (Hampson) (Lepidoptera: Noctuidae).

Malik *et al.* (2017) noted reduced adult longevity in *S. litura* at neem oil concentrations (500-2500 ppm), with the longest lifespan at 11.83 days in the control. Pineda *et al.* (2009) reported decreased longevity in *S. littoralis* adults exposed to azadirachtin (1-100 ppm).Neem-based formulations (Neenmax, Emulzinim, Nim-I-go) reduced longevity in *H. armigera*adults, with males and females living shorter lives than the control (Farias *et al.,* 2019). Abedi *et al.* (2014) found azadirachtin reduced adult longevity in *H. armigera* by 18.1% and Pineda *et al.* (2007) reported a similar effect in *S. littoralis*.

Singh *et al.* (2006) observed reduced adult longevity in *P. xylostella* treated with *M. azedarach* extract. Schmidt *et al.* (1997) found *Melia* extract decreased male and female longevity in *S. littoralis* and *A. ipsilon* was similarly affected, with significant reductions at higher concentrations.

Sub-lethal influences of different botanicals on various reproductive parameters

Sub-lethal effects are defined as biological, physiological, demographic or behavioural effects on individuals or populations that survive exposure to a toxicant at lethal or sub-lethal concentration. A sub-lethal concentration causes no apparent mortality in the test group (Inbar and Gerling 2008). Insecticide concentrations below the median lethal (LC_{50}) are called sub-lethal in general. Life expectancy, development rates, population expansion, fertility, fecundity, changes in sex ratio, malformations and changes in behaviour, feeding, searching and oviposition are all examples of sub-lethal consequences (Lee 2000). Toxicants can have both subtle and overt effects, which must be taken into information when assessing their overall impact.

Oviposition period

Bernardi *et al.* (2011) assessed NeemAzal-T/S® on bollworm, *Bonagota salubricola* (Meyrick) (Lepidoptera: Noctuidae) finding a 7.0-day reduction in oviposition period at 0.18% concentration compared to the 10.8-day control. Farias *et al.* (2019) reported Emulzinim® (0.12% azadirachtin) decreased oviposition period in *H. armigera* to 3.9 days from the 5.5-day control. Ahmad *et al.* (2015) observed a three-day reduction in *H. armigera* pre-oviposition period with neem-based products.

Ghosh *et al.* (1999) found azadirachtin negatively impacted Asturias, *Heteracris littoralis* (Ramb.) (Orthoptera: Acrididae) development, oogenesis and spermatogenesis. Ghazawi *et al.* (2007) reported a significant 36.10 to 33.60-day decline in oviposition period in *H. littoralis* nymphs treated at 25 to 75 ppm azadirachtin concentrations compared to the 70.21-day control. Schmidt *et al.* (1997) observed *Melia* extract (10, 15, 25 ppm) reducing the oviposition period by 5.6 days for *S. litoralis* and 6.4 days for *A. ipsilon*.

Fecundity

Duarte *et al.* (2019) noted *A. indica* oil at 5000, 10000 and 15000 ppm reduced *S. frugiperda* fecundity to 827.4, 729.2 and 223.5 compared to 1216.1 in the control. Malik *et al.* (2017) found neem oil concentrations (500-2500 ppm) significantly reduced *S. litura* fecundity (505.00-631.67) compared to the control (1178.00). Pineda *et al.* (2009) reported *S. littoralis* fecundity reduction to 250.8 at 100 mg azadirachtin concentration compared to the 1753.6 control.The reduced fecundity effects might be caused by azadirachtin interfering with the production of vitellogenin in developing oocytes (Kanost *et al.,* 1990, Pineda *et al.,* 2007). Ahmad *et al.* (2015) observed *H. armigera* fecundity reductions with Neemazal (378 eggs/female/generation) and other neem-based products. Pratibha (2018) found reduced *E. vittella* fecundity with neem derivatives (169.50-177.80 at 20% LC50). Gulzar *et al.* (2018) reported *E. vittella* fecundity reduction (96.83-140.89) with *A. indica* extract. Schmidt *et al.* (1997) observed reduced *S. littoralis* and *A. ipsilon* fecundity with *Melia* extract. Irigaray *et al.* (2010) reported European grape berry moth, *Lobesia botrana* Denis and Schiffermüller (Lepidoptera: Tortricidae) fecundity reduction with azadirachtin-based formulation (117.9 at 1 mg/L). Eggs laid by treated females showed embriocidal effects, which indicated azadirachtin transference through the gravid female (Mordue and Blackwell 1993, Mordue 2004, Seljansen and Meadow 2006).

Hatchability of the eggs

Schmidt *et al.* (1997) reported reduced hatchability in *S. litoralis* and *A. ipsilon* larvae treated with *M. azedarach* concentrations of 10, 15 and 25 ppm. Hatchability rates were 78.7, 28.6 and 0% for *S. litoralis* and 74.1, 52.9 and 16.7% for *A. ipsilon*, compared to 87.1% in the control.

Tirathaba rufivena (Lepidoptera: Pyralidae) eggs were treated for 24, 48 and 72 hours respectively after deposition, with the LC_{25} (11.35 mg AI/L), LC_{50} (28.79 mg AI/L) and LC_{90} (169.00 mg AI/L) concentrations of azadirachtin solution based on stomach toxicity to first instars. The significantly reduced eggs hatchability *i.e.* 88.5, 88.3 and 62.6 % after 24 hours, 85.3, 85.0 and 61.7% after 48 hours and 82.0, 88.3 and 56.6% after 72 hours were reported (Zhong *et al.,* 2017). The residual effects of azadirachtin on the egg hatchability of *T. rufivena* were tested. When applied directly to the eggs on different days after deposition, the LC_{25} and LC_{50} concentrations did not affect larval hatch, whereas the LC_{90} treatment delayed hatch from eggs treated by 1 to 3 days after deposition (Ghatak and Bhusan 1995).

Pratibha (2018) compared three bio-formulations on *E. vittella* egg hatchability: NeemGold (NG), aqueous neem leaf extract (AEN) and aqueous garlic bulb extract (AEG). NG was the most effective, followed by AEN and AEG, with 90.75% hatchability in control. The two commercial neem-based formulations (Nimbicidine and Neemazal) have the potential to be part of *E. vittella* management strategies as they significantly reduce the hatchability of eggs (25-50 %) (Bhardwaj and Ansari 2015).

Schneider *et al.* (2017) observed that neem oil extract increased the number of undeveloped eggs in American sugarcane borer, *Diatraea saccharalis* (Fabricius) (Lepidoptera: Crambidae) at concentrations of 0.3, 0.5, 1.0 and 2.0%, with undeveloped eggs at 19.07, 28.18, 45.90 and 95.95%, compared to 9.54% in control. Oliveira *et al.* (2013) also noted a prolonged embryonic period and 42.4% hatch rate with neem oil treatment in *D. saccharalis*.

Survival of the larvae

Martinez and Emden (2001) found that azadirachtin, had sub-lethal effects on the survival and development of *S. litura*. Neonate larvae exhibited moulting disruptions, morphological anomalies and increased mortality when fed an artificial diet with 0.1 to 1.0 ppm azadirachtin. Higher concentrations reduced survivability and affected developmental stages of *S. littoralis*. In fruit fly, *Drosophila melanogaster* (Frederick) (Diptera: Drosophilidae), azadirachtin significantly decreased the numbers of eggs, larvae, pupae and adults in the F1 generation at concentrations of 0.1 to 1.2 µg (Oulhaci *et al.,* 2018). Seljasen and Meadow (2006) observed that neem treatment did not affect egg hatch rates in cabbage moth, *Mamestra brassicae* (Linnaeus) (Lepidopstera: Noctuidae) but reduced larval survival after one week. Larvae on neem-treated plants remained in the first instar stage and all died within two weeks, unlike control plants with an average of 15.6 surviving larvae. All larval instars of *T. rufivena* were susceptible to azadirachtin, with higher concentrations reducing neonate larvae survival, especially those emerging from treated eggs. Survival rates dropped significantly after 24, 48 and 72 hours with LC_{25}, LC_{50} and LC_{90} concentrations (Zhong *et al.,* 2017).

Antifeedant effects of different botanicals

Azadirachtin is usually associated with marked antifeedant activity and even behavioural avoidance in a large number of insect species including hemipterans (Kumar and Poehling 2007), lepidopterans (Charleston *et al.,* 2004, Shannag*et al.,* 2015), orthopterans (Capinera and Froeba 2007), coleopterans (Baumler and Potter 2007) and dipterans (Kilani-Morakchi *et al.,* 2017).

Prasoona *et al* (2022) evaluated the antifeedant effect of several plant extracts against *S. frugiperda* under laboratory conditions. The results showed that one % neem seed kernel extract was the strongest antifeedant as compared to one % lantana leaf extract. It was found that one % neem seed kernel extract in ethyl acetate had the highest antifeedant activity (60.95 to 75.17%) against third instar larvae of *S. frugiperda* in comparison to one% lantana leaf extract in ethyl acetate (42.25 to 46.98%) after 24, 48, 72-hour treatment.

The study was conducted to evaluate the different concentrations of azadirachtin against third and fourth-instar larvae of *P. xylostella*. The choice and no-choice test methods were implied for the four different concentrations, *i.e*. 0.31, 0.50, 0.60 and 1.0% of azadirachtin. It was revealed that maximum antifeedant activity was 95% and 90% for third instar larvae at 1.0 and 0.6% concentrations and similarly, antifeedant activity in the case of fourth instar larvae was 85 and 75 % at the 0.6 and 0.5% concentrations of azadirachtin, respectively (Zada *et al.,* 2018). The primary antifeedant effect of azadirachtin seems to be mediated by gustatory chemosensillas and connected to inhibition of the rate of firing of sugar-sensitive cells of the gustatory chemoreceptors by activating bitter sensitive gustatory cells (Lee *et al.,* 2010, Weiss *et al.,* 2011, Delventhal and Carlson 2016, Morakchi *et al.,*2021). The sensitivity to the primary antifeedant, azadirachtin was reported in different species. The insects avoided the ingestion of this biopesticide and preferred starving to death (Mordue and Nisbet, 2000). The internal response of a mechanism called secondary antifeedant, including a long-term reduction in food intake and toxic effects on different insect tissues (muscles, fat body and gut epithelial cells) was also reported (Mordue *et al.,* 2004; Khosravi and Sendi, 2013; Shannag *et al.,* 2015).

The study on the antifeedant effect of *A. indica* leaf extract was carried out using the no-choice leaf disc test, with different extract concentrations of 0.5, 1, 5 and 10 % against the mealworms, *Tenebrio molitor* (Linnaeus) (Coleoptera: Tenebrionidae). The feeding was inhibited in the case of all three *A. indica* leaf extracts. It was observed that ethyl acetate extract possessed more antifeedant activity than methanol extract and n-hexane extract of *A. indica* (Saidi and Nasution, 2018).

Third-instar larvae of *S. littoralis* orally treated with sub-lethal concentrations of azadirachtin display a reduction in food intake, conversion efficiency and feeding behaviour (Martinez and van Emden, 1999). In second instar larvae of *Spodoptera eridania* (Lepidoptera: Noctuidae), short-term consumption (2 days) of food treated with Azatrol, a commercial formulation of azadirachtin, reduced relative consumption rate, the efficiency of conversion of ingested food, relative growth rate, approximate digestibility and assimilation rate of food during the entire larval developmental period (Shannag *et al.,* 2015).

The biological activity of neem on the red pumpkin beetle, *Aulacophora foveicollis* (Lucas) (Coleoptera: Chrysomelidae), was studied. The effective concentration for 50% antifeedant activity was 0.01% methanolic neem seed kernel extract (NSKE) and 0.4% neem oil, using leaves of muskmelon as feeding substrate. The antifeedant activity of NSKE was found to vary with cucurbitaceous hosts. These results show that methanolic NSKE was approximately 40 times more effective than neem oil (Gujar and Mehrotra 1988). Similar studies using choice and no-choice test conditions were reported for *S. litura* by Shin and Zhang (1984).

CONCLUSION

The challenges of sustainable agriculture and environmental stewardship, the exploration of botanical insecticides like azadirachtin offers a promising avenue for the development of effective, environmentally friendly pest control methods. Continued research and application of such natural compounds can contribute to a more sustainable and ecologically balanced approach to pest management in agriculture.

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Conflict of interest

There is no conflict of interest between authors.

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